Intelligent Sensors with Application to the Identification of Structural Modal Parameters and Steel Cable Forces

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Abstract

Wireless sensing systems have been proposed for structural heath monitoring in recent years. While wireless sensors are cost-competitive compared to tethered monitoring systems, their real merit lies in their embedded computational capabilities. The academic wireless sensing prototype co-developed at Stanford University and the University of Michigan is characterized by a powerful computational core and low power consumption characteristics. In this paper, two embedded engineering algorithms, namely the fast Fourier transform and peak-picking algorithm, are implemented in the wireless sensing and validated by laboratory and field experimental studies. Moreover, the wireless sensors are applied to the problem of identifying structural modal parameters and forces in bridge steel cables. Identification results derived from the wireless sensor using the computing core are compared with those obtained by off-line engineering analysis of the measured time-history data. Such a comparison serves to validate the effectiveness of the powerful computational core of the intelligent wireless sensor. It is shown that self-interrogation of measurement data using the two embedded algorithms greatly reduces the amount of data to be transmitted by the wireless sensing network. Thus, the wireless sensor offer scalable network solutions that are power-efficient.

Introduction

Traditionally, structural monitoring systems require extensive length of cables to transmit recorded data from multiple sensors to a centralized data repository where data is warehoused. Installation and maintenance of such wired monitoring system on large-scale civil structures including high-rise buildings and long-span bridges, is time consuming and expensive; these attributes limit the adoption of the technology by the professional engineering community. With the development of wireless communication, wireless monitoring systems have been proposed to eradicate the extensive lengths of wires associated with tethered systems (Spencer *et al*. 2004, Lynch *et al.* 2005). In recent years, a plethora of academic and commercial wireless sensing systems have been developed (Lynch *et al.* 2005, Wang *et al.* 2006a). Among them, the academic wireless sensing unit prototype co-developed Stanford University and the University of Michigan (Lynch *et al.* 2003, 2005, Wang *et a*l. 2006a) has received great attention as it emphasizes a design of a powerful computational core that can process measurement data at the sensor itself (Glaser *et al.*, 2007). The data acquisition capabilities of this academic wireless sensing system has been investigated through many laboratory and field experimental studies. In these studies, the measured data collected by the wireless sensing units are in complete agreement with those collected by a traditional wire-based data acquisition system (Lynch *et al.* 2006, Wang *et a*l. 2006b and Lei *et al*. 2007)..

While the sensors offer accurate data collection, transmitting all the measured data to a single server in the data acquisition system can be difficult due to the limitations imposed by the fixed bandwidth of the wireless communication channel. Sending a tremendous amount of raw data to such a central server is also excessive in consuming power; minimization of power is critical since most sensors operate on a portable battery supply. Therefore, it is essential to embed data processing algorithms in the sensor's microprocessor, thereby allowing the senor to self-interrogate measurement data instead of directly transmitting the recorded data to a central server (Lynch *et al.* 2005, Wang *et a*l. 2006a). By conducting a portion of the computation at the sensor, only limited information needs to be transmitted back to a central station. So far, a number of data processing and analysis algorithms have been implemented in the wireless sensing units (Lynch *et al.*, 2003, 2005), but their performances still needs to be validated by various field tests on different structures.

In this paper, two embedded engineering algorithms already implemented in the wireless sensor (*i.e.*, the fast Fourier transform (FFT) and peak-picking (PP) algorithms) are modified and validated by laboratory testing of a three-story structural model. In addition, field experimental studies are carried out on a steel arch bridge under ambient vibration. Moreover, the algorithms are employed to identify the modal parameters of the building model in the lab and the cable forces in the steel arch bridge. Identification results from the intelligent wireless sensors are then compared to those obtained by off-line engineering analysis of the measured raw time-history data. This side-by-side comparison of modal parameters allow the accuracy of the embedded algorithms to be tested.

Wireless sensing units

The academic wireless sensing unit prototype co-developed at Stanford University and the University of Michigan by Wang, Lynch, Law *et al.* (2006a) consists of three main functional modules: (1) sensing interface, (2) computational core, and (3) wireless communication module, as shown in Figure 1. In this paper, the research focus is placed upon the software that is embedded in the microcontroller core. As shown in Figure 2, the embedded software is structured using a multi-layer approach. At the lowest layer of the embedded software architecture is the real-time operating system (OS) which directly operates the wireless sensor hardware. Software that manages and processes sensors data resides on a second tier of the software architecture; it is these processing algorithms which grants the wireless sensor its "smart" characteristics. A number of data processing and analysis algorithms, including the FFT and PP schemes, have previously been embedded in

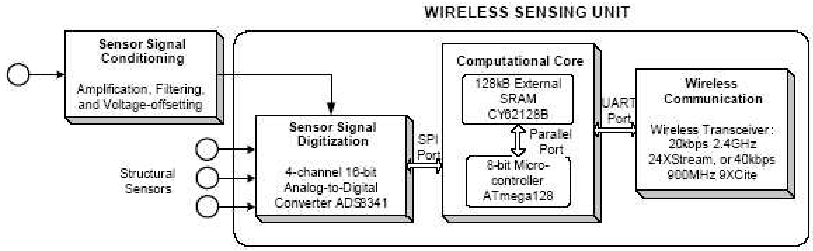

Figure 1. The academic wireless sensing unit

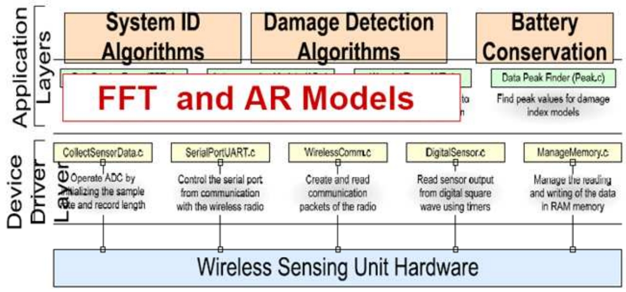

Figure 2. Embedded software model for the wireless sensors

the computational core of the wireless sensors.. The algorithms are coded in the programming language C (Lynch *et al*., 2003, 2005). The approach of leveraging the computational core to locally process data is significantly more power efficient than wirelessly transiting long records of raw time history data to the data repository.

Laboratory experimental studies

The performance of the wireless monitoring system is first studied by installing the wireless sensing units upon a three-story test structure constructed in the laboratory. The structural model behaves as a lumped-mass shear structure because of its rigid floors and flexible columns. At each floor level, a wireless sensing unit is mounted as shown in Figure 3. Acceleration responses of the structure due to sweep sine excitation at the base are recorded by the wireless sensing system. The time-history response data is transferred to the frequency domain through the use of the embedded FFT algorithm. Specifically, a 4096-point complex-valued Fourier spectrum is obtained. To compare the accuracy of the embedded FFT algorithm, the frequency spectrum calculated by the wireless sensing unit at the second floor is compared with that estimated offline by MATLAB using the same raw time history response used by the wireless sensor. As shown in Figure 4, the online FFT and offline FFT values are in close agreement.

The peak-picking (PP) algorithm previously embedded in the wireless sensing units are modified for picking high valued spectrum peaks and sending the complex valued peaks to the server. When a structure is lightly damped and the modes are well separated, it is known that modal frequencies of the structure can be estimated from the frequencies corresponding to the spectrum peaks. Also, under sweep sine excitation, the Fourier spectra calculated from the acceleration response data by the embedded FFT algorithm can be considered as the frequency response function (FRF) of the structure. Furthermore, the mode shapes can be determined based upon the imaginary components of the different FRF function at the peaks:

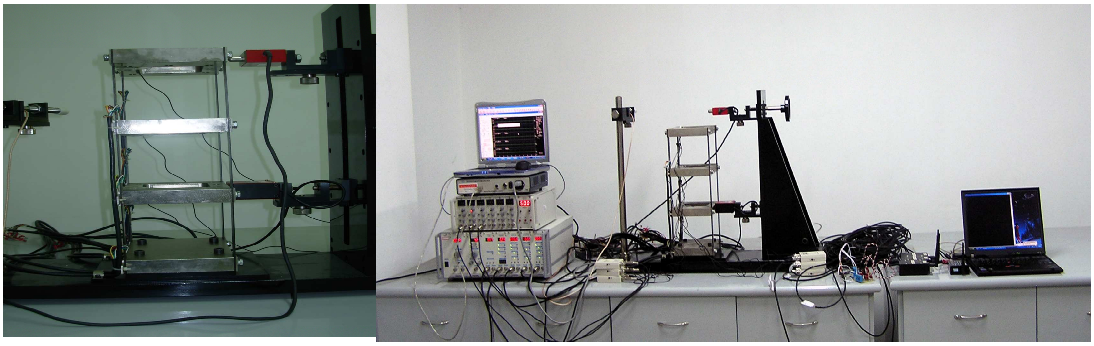

Figure 3. Test structure model with wireless sensing system

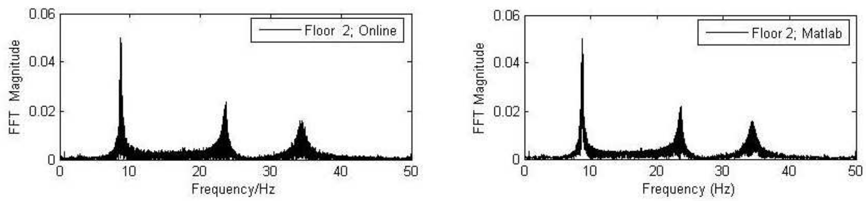

Figure 4. Comparison of online (left) and off-line (right) FFT

$$\{\phi_j\} = \{\mathrm{Im}[H_1(i\omega_j)], \mathrm{Im}[H_2(i\omega_j)], ..., \mathrm{Im}[H_n(i\omega_j)]\}^T \qquad (1)$$

where $H_k(i\omega_j)$ is the FRF of the structure at sensor location *k*, *n* is the number of total sensors installed on the structure, and Im[•] denotes the imaginary component of [•].

To check the accuracy of the embedded PP algorithm, the results transmitted to the central data repository are compared with those obtained from an off-line FFT and PP analysis of the same time-history data. As shown in Table 1, the modal frequencies and the imaginary components of the FRF at those frequencies estimated from the two approaches are identical.

Second, to confirm the accuracy of the estimated modal frequencies and mode shapes, the measured time-history data wirelessly transmitted to the central data repository is used in the advanced stochastic subspace identification (SSI) algorithm, an effective time domain system identification approach, to identify the modal frequencies and mode shapes of the structure. As shown in Table 2, the modal frequencies and mode shapes identified by the PP

	Embedded PP						PP off-line					
	1st Peak		2nd Peak		3rd Peak		1st Peak		2nd Peak		3rd Peak	
	Freq.	Im(H)	Freq.	Im(H)	Freq.	Im(H)	Freq.	Im(H)	Freq.	Im(H)	Freq.	Im(H)
1st Floor	8.30	-68.77	23.9	-96.91	34.47	27.50	8.30	-68.77	23.9	-96.91	34.47	27.5
2nd Floor	8.30	-119.8	23.9	-47.26	34.47	-42.8	8.30	-119.8	23.9	-47.26	34.47	-42.8
3rd Floor	8.30	-152.5	23.9	82.58	34.47	19.24	8.30	-152.5	23.9	82.58	34.47	19.24

Table 1. Comparison of the results obtained by the embedded and offline PP analyses

	Mode 1		Mode 2		Mode 3	
	PP	SSI	PP	SSI	PP	SSI
Frequency (Hz)	8.30	8.31	23.90	23.59	34.47	34.54
1st Floor Modal Component	0.451	0.450	-1.174	-1.177	1.429	1.839
2nd Floor Modal Component	0.786	0.786	-0.572	-0.545	-2.224	-2.24
3rd Floor Modal Component	1.000	1.000	1.00	1.000	1.000	1.00
MAC	1.000		0.998		0.978	

Table 2. Comparison of identified modal frequencies and mode shapes

Figure 5. (Left) Side view of the Wuyuan Bridge; (right) employed wireless sensors on the bridge

algorithm are in close agreement with those from the SSI analysis except for minor discrepancies in the 3rd mode shape. This minor discrepancy is due to the fact that PP is a simple but not so accurate approach to estimating mode shape of a structure. Modal assurance criteria (MAC) are used to quantify the similarity between identified modes.

The embedded PP algorithm in the wireless sensors first identifies the modal frequencies of the structure. Then, the sensors transmit the imaginary components at those frequencies to the central data repository where normalized mode shapes of the structure are estimated. This approach is inherently decentralized and well suited for the distributed computing paradigm offered by the embedded algorithm. It is also a power-efficient approach as the long records of time-history data do not need to be wirelessly transmitted; rather, only the estimated imaginary components of the FRFs at each sensor location are transmitted.

Field experimental studies – Wuyuan Bridge

Field experimental studies provide a more realistic way to assess the performance of the wireless monitoring system. The wireless sensing system is installed upon the Wuyuan steel arch bridge. The bridge shown in Figure 5 is a half-through basket type arch bridge. The main span is 210 m long with the main deck supported by hangers from the arched ribs. The wireless sensing systems employs accelerometers to measure the vertical and transverse responses of the bridge deck and the arched ribs, as indicated by Figures 5.

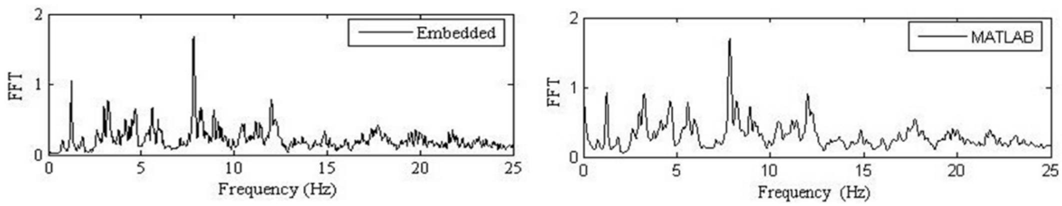

Figure. 6 Comparison of embedded and off-line FFT of sensor at location #5

Frequencies	Embedded PP	Off-line Results

Acceleration responses of the bridge under ambient excitation are recorded by the wireless sensing system. Then, the frequency spectra are calculated by the embedded FFT algorithm in the sensors. For validation of the embedded FFT algorithm, the raw time histories of the acceleration response collected by the individual units are also transmitted to the central data server and transferred to frequency domain by MATLAB. As shown in Figure 6, the online FFT and offline FFT spectrum are nearly identical with only minor discrepancies evident at the lower frequencies.

Bridge cable forces are an important parameter to study for the assessment of bridge safety. Some techniques have been developed for the measurement of bridge steel cable forces. For bridges in service, steel cable forces are usually monitored by the technique based on the vibration frequencies of cables (Russell and Lardner, 1998). Based on the analysis of the transverse vibration of a steel cable, forces, *T*, in a steel cable can be approximated by

$$T = 4ml^2 \frac{f_k^2}{k^2} \tag{2}$$

where l and m are the length and the mass per unit length of the cable, respectively, and f_k is the k^{th} modal frequency of the cable. Therefore, cable forces can be estimated once the vibration frequencies of cables are identified. Due to the efficient computing approach offered by the embedded FFT and PP algorithms, modal frequencies of a cable can be identified in-situ. With this in mind, an accelerometer is interfaced to the wireless sensor unit and is attached to a hanger of the bridge under ambient vibration for measurement of cable forces, as shown in Figure 7.

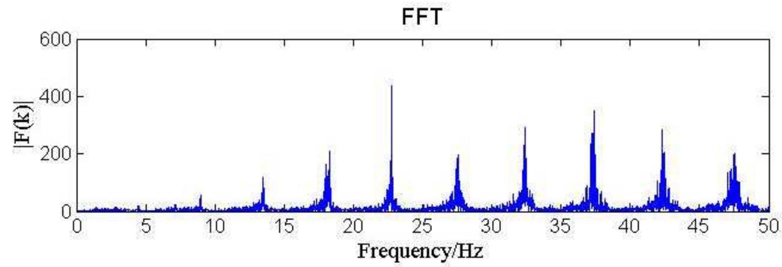

Figure 8. Frequency spectrum of the vibration of a hanger

Only the estimated modal frequencies of the cable are transmitted to the central station. The results are shown in the second column of Table 3. Although the embedded PP algorithm has been modified to capture low peaks, the amplitude of the peak at the first two modal frequencies are still too small to be identified by the automated algorithm. This is because the accelerometer is attached near the end of the hanger, so the amplitudes corresponding to the lower frequencies are small.

To validate the accuracy of the identified modal frequencies by the embedded PP algorithm, the recorded time-history data by the sensing unit are wirelessly transmitted to the central data repository where offline FFT and the SSI algorithms are applied to the data. The frequency spectrum is shown in Figure 8 and the modal frequencies identified by SSI are shown in the third column of Table 3. From the side-by-side comparison, it is evident that the embedded PP algorithm can identify the vibration frequencies of the cable accurately. With modal frequencies calculated, the force in the cable can be estimated based on frequency method as indicated by Eq. (2).

Conclusions

In this paper, two embedded engineering algorithms, the fast Fourier transform and peak-picking algorithms are implemented in an academic wireless sensor prototype and validated by laboratory and field experimental studies. It is shown that the frequency spectra calculated by the embedded FFT are accurate in both the laboratory and field studies. The embedded PP algorithm provides a simple and power-saving approach for the estimation of modal frequencies and mode shapes of structures. It can also be used to measure forces in bridge cables in a power-efficient manner. Comparison with the results obtained by off-line engineering analysis of the transmitted time-history data validates the effectiveness of the two embedded algorithms. Thus, self-interrogation of measurement data by the two embedded algorithms greatly reduces the amount of data to be transmitted by the wireless sensor network. Integrating embedded algorithms in the powerful computational cores of wireless sensors can be used for efficient identification of modal properties of structures.

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